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Emission Characteristics of Diesel Engine-Powered Cogeneration Systems

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12.1 Introduction

The industrial sector is a major electricity consumer. The growth rate of electricity demand is high especially in the developing countries and a continuous growth is anticipated for coming years. Many governments revise their energy policy introducing legislative and economic incentives to encourage private participation in the power generation investments. Generally, a favorable economic environment is created for the industries that make use of energy conservation, and cogeneration is an effective method of achieving this. Unfortunately power facilities have the potential of environmental pollution by the emission of harmful gases and other hazardous components. Power plants and cogeneration facilities emit some undesirable content in exhaust gases including solid particles, and these emissions, depending on their level, can be very harmful for human beings and other organisms (Frangopoulos, 1993; EPA, 2000).

Cogeneration or combined heat and power production (CHP) is a technology used by many industries all over the world since the beginning of the 20th century as an economic means of providing industrial plant energy requirements. Reciprocating engine-powered cogeneration systems are commonly applied in the 2.5–50 MW range for power production. They are widely available as compact, fully packaged, and skid-mounted units that are easy to install. Reciprocating engine systems usually use turbocharged, intercooled industrial engines. The main fuel used is heavy fuel oil. Natural gas, diesel oil, LPG, propane, and biogas can also be used. For the diesel engine-powered cogeneration (DEPC) applications, heavy fuel oil and natural gas are the major fuels due to lower cost and high availability (Stenhede, 2004).

A major portion of environmental pollution is caused by the exhaust emission from the internal combustion engines. The three main pollutants which are subject to exhaust emission legislation are carbon monoxide (CO), unburned

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hydrocarbons (HC), and nitrogen oxides (NO_x) (Abdel-Rahman, 1998). Normally nitrogen is very inert but at high temperatures oxygen and nitrogen get the chance to mate for the formation of NO_x as in the case of combustion processes of diesel engines. Other important pollutants contained in exhaust emissions are aldehydes (H-C-O compounds), lead components produced by use of leaded fuels, sulfur dioxide (SO_2), and particulates especially with diesel engines.

Heavy fuel oil has a high share in fossil fuel consumption especially for diesel engine-powered cogeneration applications. Two major categories of heavy fuel oil are distillate oils and residual oils. Being more viscous and less volatile than distillate oils, the heavier residual oils may need to be heated for ease of use and to facilitate proper atomization for combustion. Residual oils are used mainly in industrial applications, especially in power production facilities.

In the utilization of residual heavy fuel oils for industrial power production, two major problems arise: hazardous emissions and depletion of fuel reserves in the world. Cogeneration which generates heat and power simultaneously from same fuel supply may be the most appropriate method to address these concerns (Kaarsberg et al., 1999; Stenhede, 2004). In literature, two methods were used for measuring the effectiveness of cogeneration systems in fuel savings and emission reduction. In the first method, emissions were compared between cogeneration systems and separate power heat systems (SPHS) by using the difference between the heat rates of conventional fossil fuel-fired systems and the cogeneration systems (Kaarsberg et al., 1999; Voorspools and D'haeseleer, 2000a; 2000b). In the second method, emissions released from cogeneration systems were distributed to the products (power and heat) and compared to the conventional power and heat production systems separately (Sevilgen et al., 2003). In these studies, fuel saving analysis (FSA) was performed in terms of the first law efficiency (also called fuel utilization efficiency). The first law efficiency treats power and heat equally and this is a weakness for its use as a performance parameter for environmental studies as in the case of thermoeconomic analysis of cogeneration systems.

In this chapter, the exergetic efficiency is used for environmental assessment of the diesel engine-powered cogeneration systems. For this, emissions released from an actual diesel engine-powered cogeneration system (DEPCS) are investigated and the operations of desulfurization ($DeSO_x$) and denitrification ($DeNO_x$) units are described. The emissions assessment from DEPCS are performed by using fuel saving analysis method based on the exergetic efficiency rather than fuel utilization efficiency that is commonly used in literature. Exhaust emission reduction is expressed with an analogy to fuel savings and compared to SPHS. First, we present information on air pollution and environmental concerns in Turkey.

12.2 Air Pollution and Environmental Concerns in Turkey

Air pollution is becoming a great environmental concern in Turkey. Air pollution from energy utilization in the country is due to the combustion of coal, lignite, petroleum, natural gas, wood and agricultural and animal wastes. On the other hand, owing mainly to the rapid growth of primary energy consumption and the increasing use of domestic lignite, NO_x and SO_2 emissions, in particular, have increased rapidly in recent years in Turkey. The major source of these emissions is the power sector, contributing more than 50% of the total emissions (IEA, 2005).

12.2.1 CO_2 Emissions and greenhouse gases

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions are all produced during fuel oil combustion. Nearly all of the fuel carbon in fuel oil is converted to CO_2 during combustion process. Turkey's total carbon dioxide (CO_2) emissions amounted to 193 million tons (Mt) in 2002. Public electricity and heat production were the largest contributors of CO_2 emissions, accounting for 28% of the country's total. The industry was the second largest, representing 26% of total emissions, followed by transport, which represented 19%, and direct fossil fuel use in the residential sector with 10% (Hepbasli, 2005 IEA, 2005; Say and Yucel, 2006;). In Fig. 12.1, CO_2 emissions by fuel types between 1973 and 2002 are given (IEA, 2005). Other sectors, including other energy industries, account for 17% of total emissions. Since 1990, emissions from public electricity and heat production have grown rapidly than in other sectors, increasing by 6%. Simultaneously, the shares of emissions from the residential and transport sectors both dropped by 7% and 3%, respectively, while the share of emissions from the power production and manufacturing industries and construction sector remained stable (Hepbasli, 2005; Say and Yucel, 2006).

12.2.2 NO_x and SO_x emissions

The main air pollutants related to the power production and use of energy are sulfur oxides (SO_x) – in particular sulfur dioxide (SO_2), – nitrogen oxides (NO_x), and suspended particulates. Sulfur oxides (SO_x) emissions are generated during oil combustion from the oxidation of sulfur contained in the fuel. The emissions of SO_x from conventional combustion systems are predominantly in the form of SO_2. On average more than 95% of the fuel sulfur is converted to SO_2, about 1–5% is further oxidized to sulfur trioxide (SO_3), and 1–3% is emitted as sulfur particulate. SO_3 readily reacts with water vapor (both in the atmosphere and in flue gases) to form a sulfuric acid mist. The use of high-sulfur lignite in particular is an important source of air pollution. In 2002, Turkey emitted a total of 2.08 Mt of SO_2, equivalent to 30.4 kg per capita. This is slightly below the OECD average, which at the end of the 1990s was 32.9 kg per capita (IEA, 2005). Electricity generation and industry are by far the largest contributors to SO_2 emissions in the

country, representing respectively 65% and 21% of total emissions in 2001 (Ocak et al., 2004).

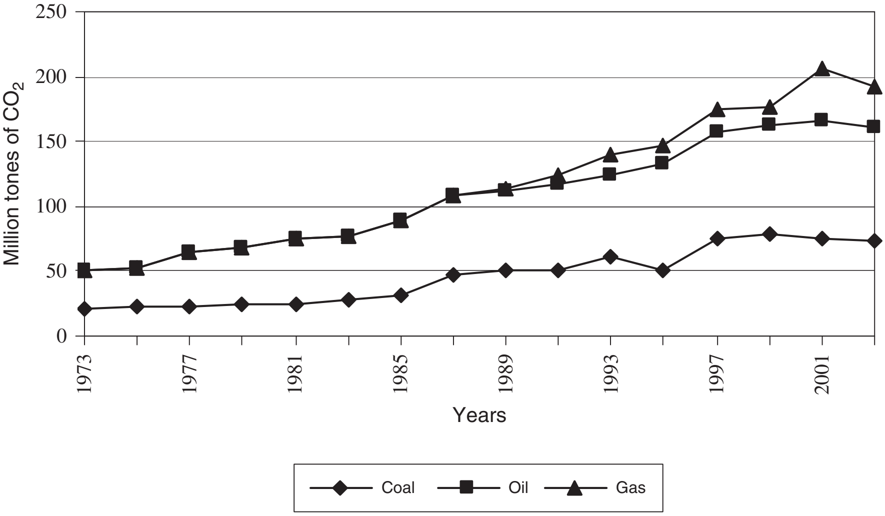

Fig. 12.1 CO_2 emissions by fuel types between 1973 and 2002 in Turkey (IEA, 2005).

The term NO_x refers to the composite of nitric oxide (NO) and nitrogen dioxide (NO_2). For most fossil fuel combustion systems, over 95% of the emitted NO_x is in the form of nitric oxide. Nitrous oxide (N_2O) is not included in NO_x but has recently received increased interest because of atmospheric effects. Emissions of NO_x totaled approximately 0.90 Mt in 2003, slightly below the 2000 levels of 0.92 Mt. On a per capita level, emissions were of 12.8 kg in 2003, substantially below the OECD average of approximately 40 kg at the end of the 1990s. Transportation and predominantly road-based transport, is the largest source of NO_x emissions, representing 36% of total emissions. Electricity generation and industry represent over 20% each (IEA, 2005; Ocak et al., 2004).

12.2.3 Particulate matter (PM) emissions

Particulate emissions maybe categorized as either filterable or condensable. Filterable particulate matter emissions depend predominantly on the grade of fuel fired. Combustion of lighter distillate oils results in significantly lower PM formation than does combustion of heavier residual oils. In general, filterable PM emissions depend on the completeness of combustion as well as on the oil ash content (EPA, 2000). The PM emitted by distillate oil-fired combustion processes primarily comprises carbonaceous particles resulting from incomplete combustion of oil and is not correlated to the ash or sulfur content of the oil. However, PM

emissions from residual oil burning are related to the oil sulfur content. This is because low-sulfur residual oil (heavy fuel oil no. 6), either from naturally low-sulfur crude oil or desulfurized by several processes, exhibits substantially lower viscosity and reduced asphaltene, ash, and sulfur contents, which results in better atomization and more complete combustion (IEA, 2005). The emission standards for power plants in Turkey are given in Table 12.1 with the revision in 2004. These standards remain significantly less stringent than those currently in force at the EU (European Union) level as defined by the revised Large Combustion Plants (LCP) directive (IEA, 2005; Ulutas, 2005). For example, for new liquid fuel-fired power plants (authorized after November 2003) with a thermal input greater than 300 MW, the NO_x emissions limit is set at 200 mg/Nm^3 at the EU level, while the NO_x emissions limit is 800 mg/Nm^3 in Turkey.

Table 12.1 Emission standards for power plants in Turkey (IEA, 2005).

1986 REGULATION (mg/Nm^3)									
	PM		CO	NO_x		SO_2			
	OP	NP		OP	NP	<300 MW$_{th}$		>300 MW$_{th}$	
						ROH>20,000	NP	ROH<50,000 and OP	ROH>50,000 and NP
SFFP	250	150	250	1000	800	3200	2000	3200	1000
LFFP	110	110	175	1000	800	3200	1700	1700	800
GFP	10	10	100	500	500	60	60	60	60
2004 REGULATION (mg/Nm^3)									
SFFP	100		200	800		2000 (<100 MW$_{th}$) 1300 (100–300 MW$_{th}$)		1000 ≥300 MW$_{th}$	
LFFP	110–170 ≥15 MW$_{th}$		150	800		1700 (1% S[a]) 2400 (1.5% S) (<100 MW$_{th}$) 1700 (100–200 MW$_{th}$)		800 ≥300 MW$_{th}$	
GFP	10		100	500		60		60	

SFFP: solid fuel-fired plants, LFFP: liquid fuel-fired plants, GFP: gas-fired plants,
OP & NP: old plants and new plants, refer to power plants built before and after Air Quality Protection regulation came into force in 1986
ROH: remaining operating hours
[a] Sulfur content (mass percentage) of the fuel used

12.3 Description of Exhaust Flow in the DEPC Plant

The actual DEPC plant, SANKO Energy, is located in the southeastern Turkey, the city of Gaziantep (Abusoglu and Kanoglu, 2008). The electricity is generated by three, diesel engine-actuated generator sets each having two turbochargers.

Each diesel engine–generator set in the plant produces 8.44 MW electricity and 2.7 tons/h saturated steam at 8 bars and 170°C. The engine operating and performance characteristics are listed in Table 12.2. For calculated engine parameters, related data can be found from related papers and reference books (Abusoglu and Kanoglu, 2008, 2009a, 2009b; Pulkrabek, 1997). The schematic diagram of the plant's exhaust flow line for one engine set is shown in Fig. 12.2. The permissible annual electricity production is 217 GWh and the annual heavy fuel oil consumption is nearly 45,000 tons at designed operating conditions.

The exhaust gases leaving the engine flow through the turbine of the turbocharger unit to produce the necessary shaft work for the compressor. The exhaust gases leaving the turbine is sent to the DeNO$_x$ (denitrification) unit in which the NO$_x$ emission is lowered to acceptable legal values by spraying urea solution onto the exhaust gases. Then, the exhaust gases leaving the turbine enter the waste heat recovery unit to transfer heat to the feedwater to produce steam for manufacturing facilities in the factory and for preheating of streams in the auxiliary equipments such as fuel forwarding module and fuel oil in daily usage tank. Finally, the exhaust gases flow through a DeSO$_x$ (desulfurization) unit before being exhausted to the atmosphere.

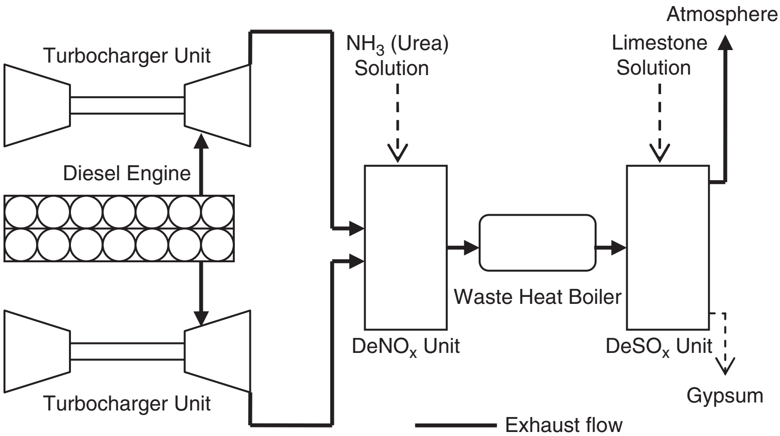

Fig. 12.2 Exhaust flow schematic of the DEPC plant. Only one engine set is shown.

12.3.1 Denitrification unit (DeNO$_x$)

The main aim of the denitrification unit is to treat NO$_x$ exhaust emissions as N_2 and water. During burning of fuel the molecules including nitrogen reacts with oxygen in the intake air and produce NO. If the amount of oxygen is less, then instead of NO, the product will be N_2. This process is the basic of the denitrification principle by improving the quality of combustion. For each engine-

generator set one DeNO$_x$ unit is installed. Casing of the units are insulated to prevent heat transfer. NO$_x$ emissions are treated into the nitrogen (N_2) and water (H_2O) by selective catalytic reduction (SCR) process. The SCR reaction is catalyzed by vanadium/titanium catalysts at temperatures in the range 300–500ºC as shown below:

$$NO_2 + NO + NH_3 \rightarrow 2N_2 + 3H_2O \tag{12.1}$$

The catalytic reactors are made of special ceramics shaped in honeycomb modules. Ammonia (NH_3) obtained from urea in liquid form is used as redactor element. The exhaust gas at 300–450ºC is transferred from cylinders to DeNO$_x$ units by insulated exhaust ducts. Exhaust gases at high temperature pass through the catalytic reactors; here NH_3 is injected into the exhaust gases, and so NO$_x$ react with NH_3 and produce nitrogen (N_2) and water (H_2O).

Table 12.2 Operating and performance characteristics of Diesel 32 V 40 engine.

Cylinder diameter, D (mm)	320
Cylinder bore, B (mm)	320
Stroke, S (mm)	400
Crank offset, a (mm)	200
Number of cylinders, N_c	18
Piston area, A_P (m²)	0.08
Compression ratio, r_c	12.37
Displacement volume, V_d (m³)	0.03217
Clearance volume, V_c (m³)	0.00283
Air flow rate, $\dot{m}_a$ (kg/s)	18.4
Fuel flow rate, $\dot{m}_f$ (kg/s)	0.46
Air–fuel ratio, AF	40.0
Exhaust flow rate (kg/s)	17.0
Piston mean speed, U_p (m/s)	10.0
Engine speed, N (rpm)	750
Break power, $\dot{W}_b$ (kW)	8440
Brake mean effective pressure, bmep (kPa)	2490
Torque, τ (Nm)	114.6
Brake-specific fuel consumption, bsfc (g/kWh)	184.0
Specific power, SP (kW/m^2)	6217
Specific volume, SV (m^3/MW)	0.06434
Output per displacement, OPD (kW/L)	14.58
Combustion efficiency, η_c	0.98
Volumetric efficiency, η_v	1.29
Thermal efficiency, η_{th}	0.47

These two final products are natural materials and have no harmful effect on the environment. The total solid urea consumption of $DeNO_x$ unit is about 260 kg/h, where total NO_x mass flow is 402 kg/h. The treated flue gas should include NO_x at a total amount less than 800 mg/Nm^3 as indicated in Table 12.1.

12.3.2 Desulfurization unit ($DeSO_x$)

From process point of view the proposed flue gas desulfurization system is referred to as "limestone–gypsum" process, based on the use of common limestone ($CaCO_3$) in powder form as reagent and the production of gypsum as by-product. The limestone consumption is nearly 750 kg/h. The waste gas purification process is performed for each gas stream in a scrubber with integrated quencher where SO_2 and other pollutants (SO_3 – HCI) are removed by washing liquid which is a suspension of limestone in water. The waste gas enters laterally above the bottom of the scrubber into the quenching zone of the scrubber. The waste air is cooled down to the saturation temperature in the quencher zone. From here the waste gas flows vertically upward to the subsequent nozzle lever where the pollutants absorption, as well as some dust separation takes place. During the absorption of SO_2, SO_3, and HF, hardly soluble deposits such as $CaSO_4$, H_20, $CaSO_3$, and CaF_2 are formed and suspended in the scrubbing solution. In order to prevent larger deposits in the scrubbing liquid tank, an agitator is installed in the scrubber sump. This serves at the same time for dispersing the oxidation air. The reaction that takes place during the desulfurization process is

$$CaCO_{3(S)} + SO_{2(g)} + 0.5H_2O \Rightarrow CaSO_3.0.5H_2O + CO_{2(g)} \tag{12.2}$$

When the oxidation with air take place

$$CaCO_{3(S)} + 0.5H_2O_{(l)} + 1.5H_2O_{(g)} \Rightarrow CaSO_4.2H_2O_{(s)} \tag{12.3}$$

Due to the continuous recirculation and subsequent formation of some sulfites and sulfates a portion of recirculated liquid is bled off to a dewatering system that provides a reduction of moisture down to 15% residual water content, in order to handle the gypsum removal. The scrubbing and cooling liquid suspension is accumulated in the scrubber lower sump from where it is taken and recirculated by suitable wear-resistant recirculation pumps. The treated flue gas should include SO_2 at a total amount less than 2400 mg/Nm^3 (see Table 12.1). In Tables 12.3 and 12.4, emission content of exhaust gases before and after the flue gas treatment units ($DeNO_x$ and $DeSO_x$) are given.

12.4 Fuel Savings Analysis

The diesel engine-powered cogeneration system (DEPCS) converts waste heat, which is a consequence of electricity production by diesel engines, to useful heat. In these systems, the conversion ratio of fuel chemical or heat energy to electrical energy can be defined as electricity (or thermal – first law) efficiency η_e and the

conversion ratio to heat energy is defined as heat efficiency η_h. Electricity and heat generation are denoted by $\dot{W}$ and $\dot{Q}$, respectively.

Table 12.3 Emission content of exhaust gases before the flue gas treatment for the DEPC plant.

Content	Engine 1	Engine 2	Engine 3
O_2 (%)	13.40	13.45	13.55
CO_2 (%)	5.55	5.55	5.45
CO (mg/m^3)	75.5	90	105
NO (mg/m^3)	1485	1500	1532
SO_2 (mg/m^3)	935.5	1149	1053
Gas temperature (°C)	309.5	312.5	310

In separate power heat systems (SPHS), separate fuels are used to obtain electricity and heat. Fuel consumption in these systems was treated as dependent parameter on electricity generation system efficiency η_{se} and boiler heat efficiency η_{sh} in literature (Kaarsberg et al., 1998, 1999, Voorspools and D'haeseleer, 2000a, 2000b; Sevilgen et al., 2003).

Table 12.4 Emission values of exhaust gases after the flue gas treatment for the DEPC plant.

Type of fuel	Fuel oil no. 6
Power produced (MW)	25.32
Exit exhaust temperature (ºC)	53.7
Velocity of exhaust gas at the exit (m/s)	8.1±0.1
Mass flow rate of exhaust gas at the exit (m^3/h)	123,464
Particulate matter concentration (mg/m^3)	96.78
Particulate matter emission (kg/h)	11.8695±2.6904 (limit value: 15)
CO concentration (mg/m^3)	101.67
CO emission (kg/h)	12.5507±1.4898 (limit value: 5)
SO_2 concentration (mg/m^3)	40.95
SO_2 emission (kg/h)	5.0673±0.6036 (limit value: 100)
NO concentration (mg/m^3)	1282.14
NO emission (kg/h)	158.3056±18.7665 (limit value: 20)
NO_2 concentration (mg/m^3)	1983.75
NO_2 emission (kg/h)	244.94
O_2 concentration (%)	12.8
CO_2 concentration (%)	6.3

In the analysis of fuel savings, the exergetic efficiency is used for environmental assessment of DEPCS system versus SPHS. In comparing DEPCS and SPHS, it is assumed that they produce the same amount of electricity and heat. Electricity and heat generation are calculated from

$$\dot{W} = \dot{m}_{\mathrm{f}} LHV_{\mathrm{f}} \varepsilon_{\mathrm{e}} \tag{12.4}$$

$$\dot{Q} = \dot{m}_{\mathrm{f}} LHV_{\mathrm{f}} \varepsilon_{\mathrm{h}} \tag{12.5}$$

where LHV_{f} is the lower heating value of the fuel, $\dot{m}_{\mathrm{f}}$ is the rate of fuel used, ε_{e} and ε_{h} are the exergetic efficiencies of DEPCS in terms of electric power produced and steam generated, respectively. The amount of fuel required to produce the same amount of electricity in SPHS can be determined from

$$\dot{m}_{\mathrm{sef}} = \dot{m}_{\mathrm{f}} \zeta_{\mathrm{e}} \left(\frac{\varepsilon_{\mathrm{e}}}{\varepsilon_{\mathrm{se}}} \right) \tag{12.6}$$

where ζ_{e} is the ratio of the lower heating value of the fuel used in DEPCS to the lower heating value of the fuel used in SPHS, and $\varepsilon_{\mathrm{se}}$ is the exergetic efficiency of SPHS in terms of power produced. The amount of fuel required to produce heat in the boiler, which is equal to the heat produced in DEPCS, is calculated from

$$\dot{m}_{\mathrm{shf}} = \dot{m}_{\mathrm{f}} \zeta_{\mathrm{h}} \left(\frac{\varepsilon_{\mathrm{h}}}{\varepsilon_{\mathrm{sh}}} \right) \tag{12.7}$$

where ζ_{h} is the ratio of the lower heating value of the fuel used in DEPCS to the lower heating value of the fuel used in the boiler of SPHS, and $\varepsilon_{\mathrm{sh}}$ is the exergetic efficiency of SPHS in terms of steam generated. The amount of fuel savings in this case can be expressed as (Kaarsberg et al., 1999)

$$\Delta \dot{m} = \dot{m}_{\mathrm{f}} \left[\zeta_{\mathrm{e}} \left(\frac{\varepsilon_{\mathrm{e}}}{\varepsilon_{\mathrm{se}}} \right) + \zeta_{\mathrm{h}} \left(\frac{\varepsilon_{\mathrm{h}}}{\varepsilon_{\mathrm{sh}}} \right) - 1 \right] \tag{12.8}$$

The limit condition in Eq. (12.8) that needs to be satisfied to obtain fuel savings in DEPCS is

$$\left[\zeta_{\mathrm{e}} \left(\frac{\varepsilon_{\mathrm{e}}}{\varepsilon_{\mathrm{se}}} \right) + \zeta_{\mathrm{h}} \left(\frac{\varepsilon_{\mathrm{h}}}{\varepsilon_{\mathrm{sh}}} \right) \right] > 1 \tag{12.9}$$

In case of using the same fuel in both systems $\zeta_{\mathrm{e}} = \zeta_{\mathrm{h}} = 1$, and Eq. (12.9) becomes

$$\left(\frac{\varepsilon_{\mathrm{e}}}{\varepsilon_{\mathrm{se}}} \right) + \left(\frac{\varepsilon_{\mathrm{h}}}{\varepsilon_{\mathrm{sh}}} \right) > 1 \tag{12.10}$$

The required data and the results of thermodynamic calculations for DEPCS are given in Table 12.5 (Abusoglu and Kanoglu, 2008, 2009a, 2009b). For SPHS, required data is taken from literature (Sevilgen et al., 2003). The net electrical power produced and steam generated for DEPCS are 25,320 kW and 176.1 kW, respectively. The mass flow rate of fuel oil in DEPCS is 1.38 kg/s (see Table 12.5).

Using the equations in this section, the mass flow rates of fuel for the power production unit and the boiler unit of SPHS are determined to be 1.66 kg/s and 0.20 kg/s, respectively. It is clear that using separate units of power and heat production increases the fuel consumption by 34.8% with respect to the existing DEPCS.

Table 12.5 The data of the DEPC plant for the fuel savings analysis (Abusoglu and Kanoglu, 2008, 2009a, 2009b).

Mass flow rate of fuel oil (kg/s)	1.38
Lower heating value of fuel oil (kJ/kg)	42,700
Power produced (MW)	25.32
Generated steam output (kW)	176.1
Mass flow rate of exhaust gas (kg/s)	51.0
Exergetic efficiency of DEPC plant, ε_e (%)	40.6
Exergetic efficiency of diesel engine, ε_{DE} (%)	40.4
Exergetic efficiency of waste heat boiler, ε_h (%)	11.4

12.5 Emission Difference Analysis

The amount of emission produced depends on the electricity production in DEPCS while it depends on both electricity and heat generation in SPHS. The amount of emission released by DEPCS is calculated from

$$M_{DEPC,i} = \dot{W}\theta_{DEPC,i} \tag{12.11}$$

where θ_{DEPC} stands for the specific emission of DEPCS (amount of emission released per unit electricity production) and "i" represents emission type (CO_2, SO_2, and NO_x). Emission amounts of SPHS for electricity and heat production are given respectively as (Kaarsberg et al., 1999)

$$M_{SP,i} = \dot{W}\theta_{SP,i} \tag{12.12}$$

$$M_{SH,i} = \dot{Q}\theta_{SH,i} \tag{12.13}$$

where $M_{SP,i}$ and $M_{SH,i}$ are emission amounts of SPHS for power and heat production respectively, and θ_{SP} and θ_{SH} are the specific emissions of power and heat produced in SPHS, respectively. The amount of emission reduction (ΔM) owing to DEPCS is given by

$$\Delta M = \dot{W}\left(\theta_{SP,i} + \beta\theta_{SH,i} - \theta_{DEPC,i}\right) \tag{12.14}$$

where β is the heat–power ratio (ratio of heat energy to electrical energy in the cogeneration system). The limit condition for the emission reduction is given as

$$\theta_{SP,i} + \beta\theta_{SH,i} > \theta_{DEPC,i} \tag{12.15}$$

When specific emissions are constant, a change in heat–power ratio will change the emission reduction provided by DEPCS or any cogeneration facility. The heat–power ratio for the case of equal emission production from the DEPC and SPH systems is defined as critical heat–power ratio β^* and expressed as

$$\beta^* = \frac{\theta_{\mathrm{DEPC,i}} - \theta_{\mathrm{SP,i}}}{\theta_{\mathrm{SH,i}}} \tag{12.16}$$

Average specific emissions of the DEPC plant can be obtained using the values in Table 12.5. For SPHS, these values can be taken from literature (Kaarsberg et al., 1998, 1999; Voorspools and D'haeseleer, 2000a, 2000b; Sevilgen et al., 2003). Table 12.6 contains specific emissions for gas turbines, DEPC, and gas engines for both cogeneration and conventional power plant applications. Comparison of these specific emissions and the efficiencies of the DEPC and SPH systems are given in Figs. 12.3 and 12.4, respectively. Exergetic efficiencies and the heat–power ratio of the DEPC plant are given in Table 12.7. Natural gas, lignite, and heavy fuel oil are considered as fuels in boilers used for heat production in SPHS and average specific emissions of these fuels are shown in Table 12.8.

Table 12.6 Specific emissions of various cogeneration plants and conventional power plants (g/kW$_e$h) (Kaarsberg et al., 1998, 1999; Voorspools and D'haeseleer, 2000a, 2000b; Sevilgen et al., 2003).

Emission	Cogeneration systems			Conventional power plants	
	Gas turbine	DEPC	Gas engine	SPH	Combined cycle
NO_x	0.25	0.41	1.34	3.3	0.18
CO_2	580	500	529.1	997.3	400
SO_2	–	2.20	–	3.7	–

By using the emission values in Table 12.4, the amount of each emission can be calculated for DEPCS for full load power production as 10.381 kg for NO_x, 12.66 m^3 for CO_2, and 55.704 kg for SO_2. Corresponding values for SPHS owing to the same amount of power produced and steam generated as DEPCS are determined, respectively, as 83.56 kg and 0.110 kg for NO_x, 25.25 m^3 and 0.05 m^3 for CO_2, and 93.68 kg and 1.28 kg for SO_2. It is clear that the DEPC plant can reduce NO_x, CO_2, and SO_2 emissions by 87.6%, 50% and 41.3%, respectively, in comparison to SPHSs.

Table 12.7 Exergetic efficiencies and heat–power ratios for the DEPCS and SPHS (Abusoglu and Kanoglu, 2008, 2009a, 2000b; Sevilgen et al., 2003).

	ε	β
DEPC	0.404	0.007
SPHS		
Steam turbine power system	0.334	–
Combined cycle system	0.480	–
boiler	0.770	

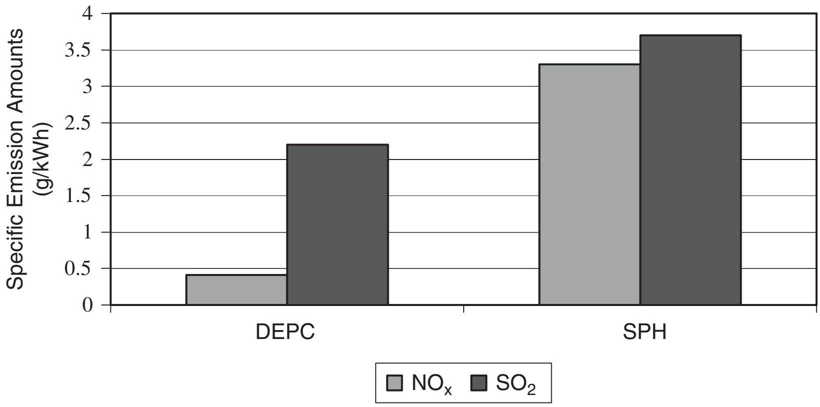

Fig. 12.3 NO_x and SO_2 emissions comparison of DEPC and SPH at full load condition.

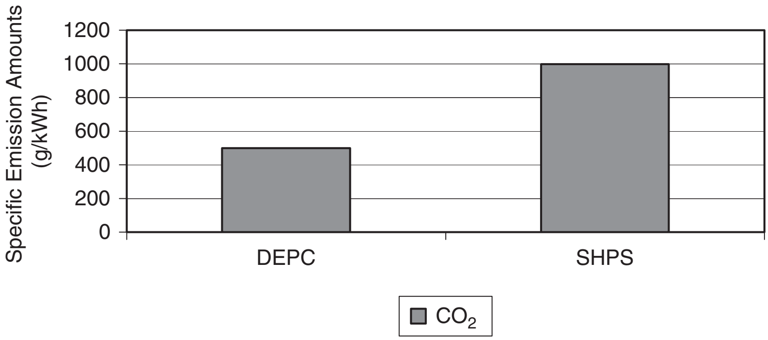

Fig. 12.4 CO_2 emissions comparison of DEPC and SPH at full load condition.

Table 12.8 Emissions produced in boiler for producing heat (g/kWh) (Kaarsberg et al., 1999; Voorspools and D'haeseleer, 2000a, 2000b; Sevilgen et al., 2003).

Fuel type	NO_x	CO_2	SO_2
Natural gas	0.93	201.92	–
Coal (lignite)	0.89	364.25	9.21
Fuel oil no. 6	0.62	263.95	7.25

In DEPCS, amount of emissions increase with load as shown in Fig. 12.5 since specific emissions are constant. However, determining emissions reduction by using fuel savings method may cause errors because it ignores specific emission differences for different technologies utilizing the same fuel type. It can be seen that these differences are important parameters which should be taken into consideration. Parameters affecting emission differences are specific emissions, fuel type in cogeneration (i.e., emissions will be different when diesel oil or heavy fuel oil is used in DEPCS) and SPHS, and heat–power ratios of the cogeneration system.

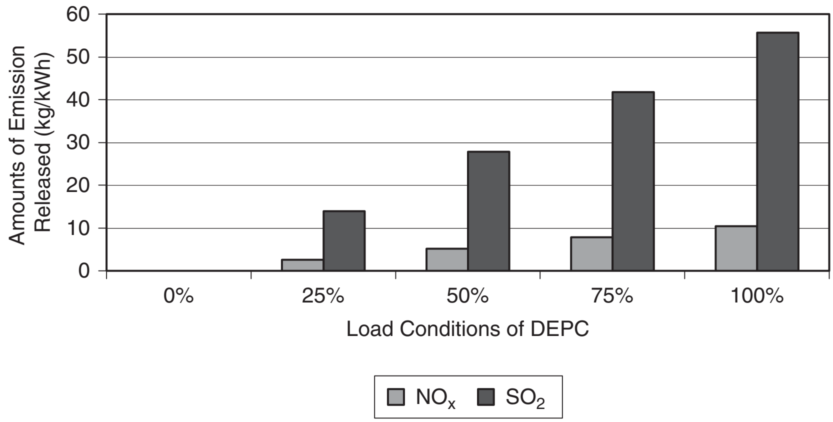

Fig. 12.5 Variation of NO_x and SO_2 emissions with respect to the load variation in DEPCS.

12.6 Conclusions

In this chapter, exhaust emission characteristics of an actual DEPC plant and the operations of denitrification ($DeNO_x$) and desulfurization ($DeSO_x$) flue gas treatment units in the facility are studied. Exhaust emission assessment is performed by using fuel savings analysis method and exergetic efficiency. Exhaust emission reduction is expressed using an analogy to fuel savings. The results show that replacing separate heat–power producing applications by cogeneration applications such as DEPC greatly reduces unwanted emissions, namely, the DEPC plant can reduce NO_x, CO_2, and SO_2 emissions by 87.6%, 50% and 41.3%, respectively, in comparison to SPHS. However, in light of actual case study presented in this chapter the following conclusions can be listed for using fuel saving analysis methodology and emission reduction:

- Emission reduction is affected by system parameters such as specific emission amounts, fuel types, cogeneration types, and different specific heat and power applications.

- Emission reduction calculated by fuel saving method can cause errors since with this method, specific emission differences are ignored for different technologies which use the same type of fuel.
- Fuel saving analysis method cannot determine the limit conditions for required emission reduction. For this reason cogeneration applications cannot always reduce emissions (Sevilgen et al., 2003).
- The emissions assessment from DEPCS is performed by using fuel saving analysis method based on the exergetic efficiency rather than fuel utilization efficiency that is commonly used in literature (Kaarsberg et al., 1999; Voorspools and D'haeseleer, 2000a, 2000b; Sevilgen et al., 2003). Exergy-based fuel saving analysis methodology usage accounts for the quality of outputs of power production systems and thus the arbitrariness of the results can be removed. However, for rational results, with the exergy-based evaluation methodologies, the allocation of emissions to the power and heat produced should be performed directly.

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Nomenclature

$\dot{W}$	power, kW
$\dot{Q}$	heat rate, kW
LHV	lower heating value, kJ/kg
$\dot{m}$	mass flow rate, kg/s
M	amount of emission (mg/Nm^3)
Greek letters	
η	first law (energy) efficiency
ε	second law (exergetic) efficiency
Θ	specific amount of emission (g/kWh)
β	heat to power ratio
β^*	critical heat to power ratio
Subscripts	
se	separate electricity
sh	separate heat
e	electricity
h	heat
f	fuel

References

Abdel-Rahman, AA (1998) On the emissions from internal-combustion engines: A review. International Journal of Energy Research, 22: 483–513.

Abusoglu, A, Kanoglu, M (2008) First and second law analysis of diesel engine powered cogeneration systems. Energy Conversion and Management, 49: 2026–2031.

Abusoglu, A, Kanoglu, M (2009a) Exergetic and thermoeconomic analyses of Diesel engine powered cogeneration: Part 1 – formulations. Applied Thermal Engineering 29: 234–241.

Abusoglu, A, Kanoglu, M (2009b) Exergetic and thermoeconomic analyses of Diesel engine powered cogeneration: Part 2 – applications. Applied Thermal Engineering 29: 242–249.

EPA Report – AP 42 (2000) Compilation of air pollutant emission factors. 5th edition, Washington DC, USA.

Frangopoulos, CA (1993), Cogeneration of heat and power – The way forward. Proceedings of a European Conference-Greek Productivity Center, Athens, Greece.

Hepbasli, A (2005) Development and restructuring of Turkey's electricity sector: a review. Renewable & Sustainable Energy Reviews 9: 311–343.

IEA (International Energy Agency) (2005) Energy Policies of IEA Countries: Turkey Review. OECD/EA, France.

Kaarsberg, T, Elliott, RN, Spurr, M (1999) An integrated assessment of the energy savings and emissions-reduction potential of combined heat and power. American Council for an Energy-Efficient Economy (ACEEE'99), Washington DC, USA.

Ocak, M, Ocak, Z, Bilgen, S, Keles, S, Kaygusuz, K (2004) Energy utilization, environmental pollution and renewable energy sources in Turkey. Energy Conversion and Management 45: 845–864.

Say, NP, Yucel, M (2006), Energy consumption and CO_2 emissions in Turkey: empirical analysis and future projection based on economic growth. Energy Policy, 34: 3870–3876.

Sevilgen, SH, Erdem, HH, Akkaya, AV, Cetin, B (2003) Comparison cogeneration system with conventional power plant and evaluation of their environmental impacts. Proceedings of the First International Energy, Exergy and Environment Symposium, İzmir, Turkey.

Stenhede, T (2004) Cogeneration and emissions. 10th International Energy and Environmental Technology Systems Fair and Conference, ICCI'2004, Istanbul, Turkey.

Ulutas, BH (2005) Determination of the appropriate energy policy of Turkey. Energy, 30: 1146–1161.

Voorspools, K, D'haeseleer, W (2000a) Dynamic simulation of the entire electric power generation system for evaluating CO_2 emissions. The Third Asia-Pacific Conference on Sustainable Energy and Environmental Technologies, Hong-Kong.

Voorspools, K, D'haeseleer, W (2000b) The impact of cogeneration in a given energetic context. 5th International Conference on Greenhouse-Gas Control Technologies (GHGT-5), Cairns, Australia.